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Effect of Interfacial Bonds on the Morphology of InAs QDs Grown on GaAs (311) B and (100) Substrates

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Abstract The morphology and transition thickness (t_c) for InAs quantum dots (QDs) grown on GaAs (311) B and (100) substrates were investigated. The morphology varies with the composition of buffer layer and substrate orientation. And t_c decreased when the thin InGaAs was used as a buffer layer instead of the GaAs layer on (311) B substrates. For InAs/(In)GaAs QDs grown on high miller index surfaces, both the morphology and t_c can be influenced by the interfacial bonds configuration. This indicates that buffer layer design with appropriate interfacial bonds provides an approach to adjust the morphologies of QDs grown on high miller surfaces.

Keywords InAs · Transition thickness · High miller index · Strain · Interfacial bonds

Introduction

Self-assembled quantum dots (QDs) have been intensively studied over the past decades in both fundamental and application fields. To date, several systems have exhibited great optical properties and find their applications, such as laser diodes [1] and optical detectors [2]. The InAs/GaAs should undoubtedly be the most widely studied one among these systems. In recent years, room temperature emission of InAs QD laser around 1.3 μm for the fiber optical communication waveband [3] and optical absorption at 8–12 μm for the long-wavelength infrared detecting [4] had been achieved by means of employing a so-called dots-

in-a-well (DWELL) structure. In this structure, the QDs are first grown on a thin InGaAs buffer layer and then finally with an InGaAs capping layer. So, the nucleation and growth dynamic of InAs QDs grown on the alloy layer are of central importance. And much attention has been paid to these important research fields [5–7].

However, most of the studies focused on the structures grown on GaAs (100) substrates. Recently, many high index polarized surfaces, such as GaAs (311) A [8] and (311) B [9–13], GaAs (411) A [14], and (411) B [15], have drawn greater attention because QDs grown on these surfaces have some unique properties, such as the narrow size distribution, high QDs density, and so on. These structure properties can further show their efforts in improving the device performances. However, the growth mechanism of QDs is still a controversial subject, especially with regard to the high index surfaces. Apparently, for the superiority of QDs grown on these high index surfaces, a deeper research into these high index surfaces grown QDs is clearly needed.

In this research, we have conducted a comparative study on the effect of buffer layer and the substrates' orientation on the equilibrium structure and the critical transition thickness (t_c) of InAs QDs grown on both GaAs (311) B and (100) substrates by molecular beam epitaxy (MBE).

Experiments

The samples were grown in a conventional MBE system equipped with 12-keV Reflection High Energy Electron Diffraction (RHEED). GaAs (311) B and (100) substrates were held side by side with indium on same molybdenum holder. For the InAs/InGaAs samples, after deoxidizing the surface oxide at 630 °C, a 500-nm GaAs buffer layer was

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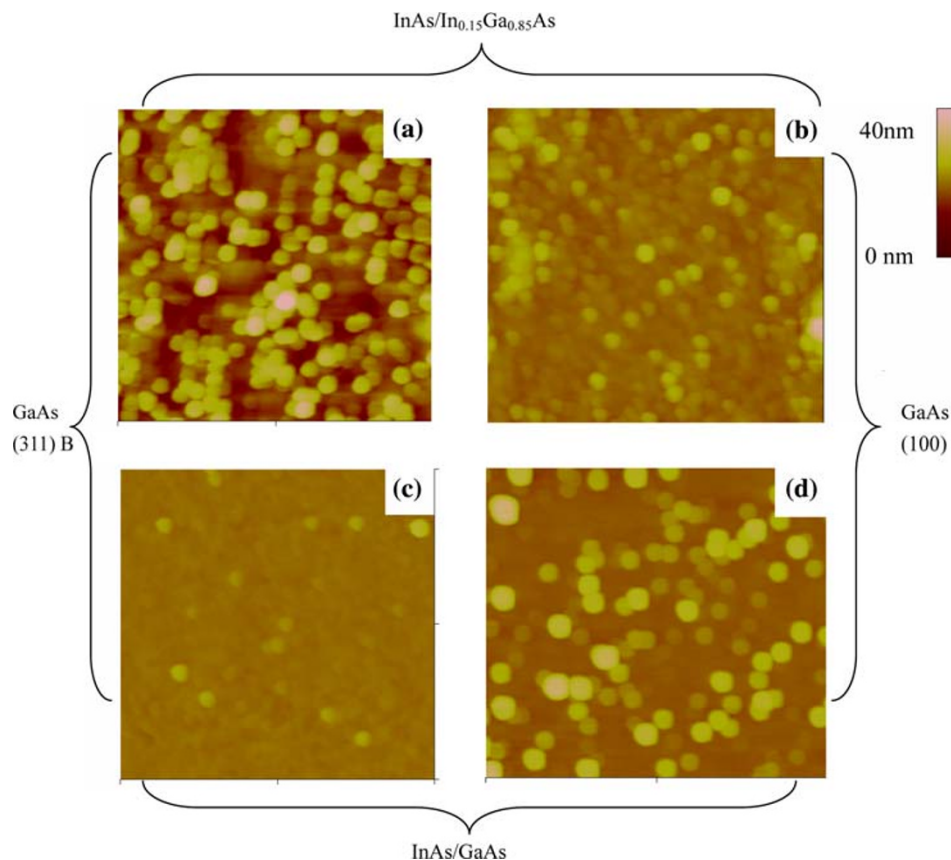
grown, then 2.3-ML InAs QDs layer was grown on top of a 2-nm $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ layer, at the rate of 0.022 ML/s. Both the QDs layer and the buffer layer were grown at 530 °C. For the InAs/GaAs samples, only the 2-nm $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ layers were changed to a GaAs buffer layer, and the coverage of InAs was 2.1 ML. As_2 was used during the whole growth process, and the As_2/In beam effective pressure–flux ratio was fixed at 40; the growth rates were determined by the RHEED oscillation technique on the (100) plane. The RHEED pattern has been imaged by a charge-coupled device camera, then digitized, and analyzed by software. When the streak pattern turned into the spots of the three-dimensional (3D) QDs which demonstrated the transition of 2D–3D growth mode, the intensity of one spotty pattern was recorded. The atomic force microscopy (AFM) test was conducted in a contact mode in air.

Results and Discussion

The surface morphology of self-assembled QDs is a key factor in determining its optical properties, and it is very sensitive to the sample structure, for example, the composition of buffer layer [16], surface reconstruction, and substrate orientation [17]. Figure 1 shows AFM images of InAs QDs grown on (In)GaAs buffer layer grown on GaAs

(311) B and (100) substrates. The morphology of QDs varies a lot with the different buffer layer and substrate orientation. Note that there are very few QDs as can be observed in Fig. 1c. This is because we reduced the InAs coverage of the InAs/GaAs samples to 2.1 ML. The purpose of this action was make sure that the InAs coverage of QDs grown on GaAs (311) B sample was just over the transition thickness (we had measured the transition thicknesses before this experiment). At the same time, the QDs on GaAs (100) had already developed for a certain time. Thus, the 2.1 ML's coverage made the difference in morphology of these two samples become more clear. For the InAs/InGaAs structures, while the QDs grown on GaAs (311) B substrates were mature, those grown on GaAs (100) substrates were clearly underdeveloped. Most of the QDs grown on GaAs (100) substrates were very small sized and only a few QDs can be clearly observed. The average density, height, lateral size, and the standard statistics error of height and lateral size of these two samples are $4.4 \times 10^{10} \text{ cm}^{-2}$ and $3.6 \times 10^{10} \text{ cm}^{-2}$; $10.3(\pm 2.58) \text{ nm}$ and $6.2(\pm 0.46) \text{ nm}$; $145(\pm 6.58) \text{ nm}$ and $130(\pm 5.8) \text{ nm}$ for the QDs on GaAs (311) B and (100), respectively. Nevertheless, for the InAs/GaAs QDs, the QDs were all of larger size on the GaAs (100) substrates than those on GaAs (311) B substrates. The average density, height, and lateral size for these two samples are $4.8 \times 10^8 \text{ cm}^{-2}$ and

Fig. 1 AFM images for InAs/ (In)GaAs QDs grown on GaAs (311) B and (100) substrates. **a** InAs/InGaAs (311) B; **b** InAs/InGaAs (100); **c** InAs/GaAs QDs (311) B; **d** InAs/GaAs QDs (100). The scan sizes were all $2 \times 2 \mu\text{m}^2$



$2.8 \times 10^9 \text{ cm}^{-2}$; $3.4(\pm 1.13)\text{nm}$ and $5.5(\pm 1.82)\text{nm}$; $105(\pm 7.1)\text{nm}$ and $159(\pm 7.0)\text{nm}$ for the QDs on GaAs (311) B and (100), respectively. These facts suggested that an earlier 2D–3D growth mode transition may exist in the InAs/GaAs on GaAs (100) than that on (311) B; however, if the buffer layer was an InGaAs layer instead of a GaAs layer, the transition starts later on GaAs (100) than on (311) B. In other words, for the InAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ samples, t_{c311} is smaller than t_{c100} ; however, for the InAs/GaAs samples, t_{c311} is larger than t_{c100} .

For the self-assembled QDs, t_c is an important parameter. For it determines when the islands were formed during the growth, which therefore has a great impact on the morphology of QDs at a given coverage. It had been confirmed that the growth parameters have very little influence on t_c . But t_c is rather sensitive to the substrate orientation, as shown by many studies that have been conducted to check the effect of substrate orientation on t_c [18, 19]. Besides, it had been found that the effect of interfacial (IF) bonds can influence t_c of the noncommon anion heteroepitaxy system ($\text{III}_1\text{V}_1/\text{III}_2\text{V}_2$, such as InAs/GaSb and InP/GaAs) greatly. Take the InAs/GaSb superlattice for example: t_c of this system was much thinner when the IF bonds consisted of In–Sb bonds rather than the Ga–As bonds [20, 21]. This is due to additional IF strain offered by the higher atom size of In and Sb than that of Ga and As. However, one cannot observe this effect for the common anion system ($\text{III}_1\text{V}/\text{III}_2\text{V}$, such as InAs/GaAs and InAs/InGaAs) because the GaAs (100) surfaces are As terminated under common growth, and the IF bond configurations are no different from those of the film [21]. So one cannot find the effect of IF bonds in the InAs/GaAs or InAs/InGaAs system grown on (100) surfaces, which is the case of our InAs/GaAs QDs grown on GaAs (100). Since the $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ layers we had grown were so thin (2 nm) that they should be fully strained, t_c should have no difference between the InAs/GaAs and InAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ samples grown on the GaAs (100) substrates [20, 21].

Then, we turn to t_c of the InAs/GaAs and InAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ structures grown on GaAs (311) B substrates. We monitored the difference in t_c of these two types of structures grown both on GaAs (311) B substrates by recording the dependence of intensity of one spotty pattern on the InAs coverage. The results can be seen in Fig. 2. A clear delay for the growth-mode transition can be found at the InAs/GaAs sample: for example, at the thickness 1.5 ML, the InAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ structure had finished the sharp rise of intensity, whereas for the InAs/GaAs structure, the transition had not even started. This result shows that t_c varies a lot according to the composition of the buffer layer at the GaAs (311) B surface.

The higher t_c of InAs/GaAs than the InAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ sample grown on GaAs (311) B can be understood by

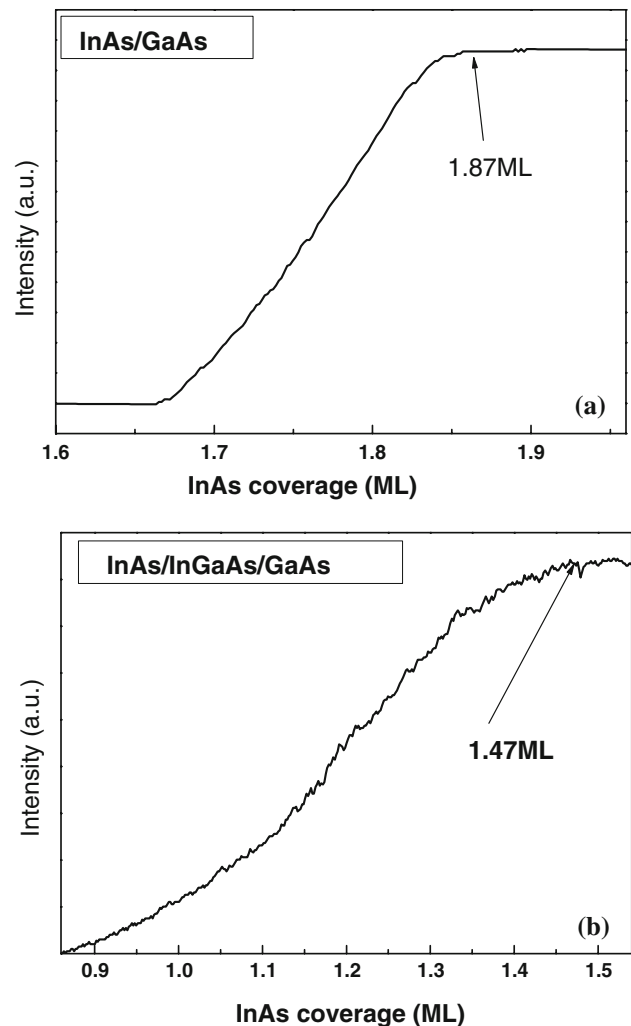
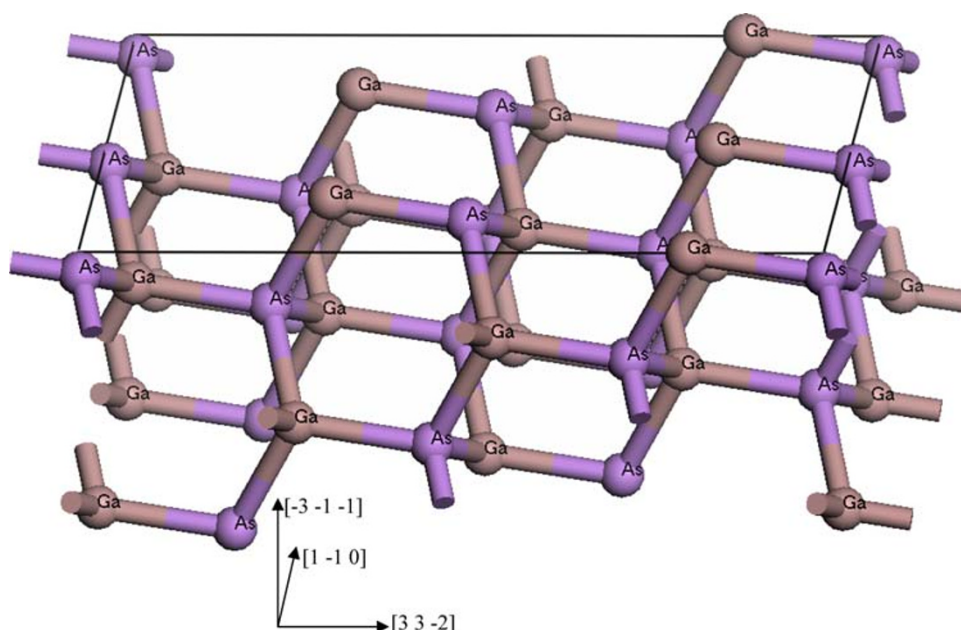


Fig. 2 The intensity of spotty RHEED pattern of sample 1 (a) and 2 (b) independent of InAs coverage

introducing the effect of IF bonds on t_c . The GaAs (311) B surface has two type of atom positions, including twofold coordinated (100)-like Ga atoms at the topmost layer (two dangling bonds) and three threefold coordinated (111) B-like As atoms at the second layer (one dangling bond); the number of these two types of position are exactly the same, as can be seen from Fig. 3 [22, 23]. If the heterointerface formed on this surface, then the IF bonds configuration is different from the film because there are mixed In–As and Ga–As bonds in the IF layer; however, only Ga–As bonds can be found in the buffer and only In–As bonds can be found in the film. So, the bonds configuration is different from the film and the buffer. Accordingly, one may see the effect of IF bonds. So, when we developed the InAs/GaAs sample, the twofold coordinated (100)-like positions were all occupied by Ga atoms, the IF bonds consisted of both Ga–As and In–As types, and the ratio between them was 2:1. While, when we developed

Fig. 3 Ball-and-stick model of the bulk-truncated GaAs (311) B surface. The numbers of Ga and As dangling bonds in the unit cell are 8 and 4, respectively



the InAs/In_{0.15}Ga_{0.85}As sample, these twofold coordinated (100)-like positions were occupied by both In atoms and the Ga atoms, and nearly 15% Ga dangling bonds were replaced by In dangling bonds. Accordingly, the ratio of Ga–As and In–As dangling bonds became lower than 2:1. Comparing to the InAs/GaAs case, the IF strain accumulated was larger due to more In–As IF bonds can be found. And the additional IF strain provided by In atoms at the buffer layer made the transition start early. So if the epitaxy is performed on a high miller index surface, the effect of IF bonds on t_c can be observed, even for the common anion systems.

Thus, when the InGaAs buffer layer was used instead of the GaAs buffer layer, t_c decreased on the GaAs (311) B substrates but remained constant on the GaAs (100) substrates. One thing that should be noted in conclusion is that the morphologies of InAs/GaAs and InAs/InGaAs QDs grown on GaAs (100) substrates are clearly very different despite the difference in InAs coverage being negligible (2.1 ML–2.3 ML). This may partly be due to the change of growth environment. After all, these two samples were not grown at the same time. Besides, this difference suggests that there may be other factors that contribute to the equilibrium shape of QDs grown on GaAs and InGaAs buffer layers: for example, the morphology differences in different buffer layers may modify the migrate length of adatoms. However, we argue that the difference in t_c still at least partly induced different equilibrium morphologies of QDs as measured by AFM. This result shows that t_c of InAs/GaAs QDs grown on high miller surfaces, i.e., GaAs (311) B, can be adjusted through modifying the type and amount of IF bonds and further to modify the equilibrium

structures. These structural characteristics would surely induce different properties. So this effect offers one parameter for the design and fabrication of self-assembled QDs, and should be regarded as an advantage for the InAs QDs grown on high miller index surfaces compared to the conventional GaAs (100) surfaces. And also, due to the often-observed morphology instability when the highly mismatched epitaxy was conducted, this study provides the information that the effect of IF bonds should be taken into consideration in this field [24].

Conclusion

In conclusion, the morphology and t_c of the self-assembled InAs QDs grown on GaAs (311) B and GaAs (100) substrates with (In)GaAs buffer layer were investigated. It was found that the configuration of IF bonds plays an important role in the morphology and t_c of InAs QDs. For common anion systems, such as InAs/(In)GaAs, this effect can only be observed at high miller index surfaces, which can be used to adjust the morphology in the QDs grown on high miller index surfaces.

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